Our share of the planetary pie

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The rise of modern agriculture and forestry has been one of the most transformative events in human history. Whether by clearing natural ecosystems or by intensifying practices on existing croplands, pastures, and forests, human land-use activities are consuming an ever-larger share of the planet's biological productivity and dramatically altering the Earth's ecosystems in the process. Although the character of land use varies greatly across the world, ranging from industrialized croplands, grazing on marginal lands, managed timber lots, animal feedlots, or biofuel plantations, the ultimate outcome is the same: the production of forest or agricultural goods for human needs taken at the expense of natural ecosystems. This observation begs the question addressed in this issue of PNAS by Haberl *et al.* (1): Just how large is the impact of human land use on the terrestrial biosphere?

Simply in terms of acreage, the answer is clear: Croplands and pastures are now among the largest ecosystems on the planet, rivaling forest cover in extent, and together occupy ≈35% of the ice-free land surface (Fig. 1) (2). Logged and managed forests add to this amount.

However, the geographic extent of managed lands is not the whole story. Although significant land-use expansion has occurred in past decades, the intensification of land-use practices under the aegis of the "Green Revolution" has increased dramatically. Simply put, many of the world's managed lands are being used more intensively as opportunities for expansion are being exhausted. For example, in the last 40 years, global crop production has more than doubled, although global cropland area has increased by only 12%, mainly through the use of high-yielding varieties of grain, massive increases (≈700%) in chemical fertilization (3, 4), increased reliance (a 70% increase) on irrigated land (5, 6), and increased mechanization. This intensification has come at a cost: Although modern agricultural practices have successfully increased food production, they have also caused extensive environmental damage (7).

Given these facts, how can we characterize the human impact on the terrestrial biosphere, including both the extent and intensity of our land-use practices?

In a landmark paper, Peter Vitousek *et al.* (8) approached this problem by estimating the human appropriation of net primary productivity (HANPP), that is, the share of global biological productivity that is used, managed, or coopted by human actions. In their analysis, Vitousek *et al.* estimated that ≈30% of Earth's terrestrial net primary productivity (NPP) is appropriated by human actions. This is an astonishing fact and has become one of the most quoted results of modern ecological science.

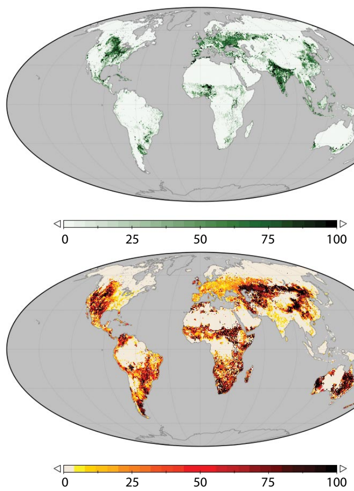

Fig. 1. Global distribution of croplands (*Upper*) and pastures and rangelands (*Lower*). Ramankutty *et al.* (2) provide the most detailed characterization of the world's agricultural land derived by combining statistical data for 15,990 administrative units of the world with satellite-based land cover data at 1-km resolution. Approximately 35% of the world's ice-free land surface was devoted to agriculture in 2000.

In the past 20 years, numerous authors have revisited the Vitousek *et al.* (8) result and have provided updates to the range of numbers reported. However, no fundamental change in the result has been reported until recently, with a series of studies that has examined the geographic patterns of the appropriation and consumption of NPP. Imhoff *et al.* (9), for example, illustrated the global patterns of human consumption of NPP based on detailed maps of population density and consumption.

Now, Haberl *et al.* (1) take the Vitousek *et al.* (8) result a major step forward by reporting the first geographically detailed analysis of the human manipulation and appropriation of terrestrial NPP. Rather than reporting a single, global-aggregate number, Haberl *et al.* now provide us with estimates of HANPP for every ≈10- × 10-km grid cell on the planet.

One of the key problems Haberl *et al.* (1) faced in documenting HANPP is first determining how human beings are changing the productivity of a given location. They illustrate how NPP has changed from both ecological degradation (i.e., from deforestation, land degradation, and soil erosion) and agricultural technology (e.g., inputs of fertilizer and irrigation water and mechanized farming). Although much of the terrestrial biosphere experiences a significant decrease in NPP from land-use practices, many regions see an increase in productivity, especially those heavily influenced by irrigation and fertilizer inputs.

These changing patterns of NPP are worth additional scrutiny. Based on an independent analysis of global cropland productivity (10) and patterns of natural ecosystem productivity (11), we see a similar pattern of productivity changes (Fig. 2). This analysis, which is based on country-, state-, and county-level agricultural data from around the world, plus a statistical analysis of ≈3,000 measurements of natural ecosystem productivity, tells the same story: Regions of high irrigation and fertilizer use show increased productivity compared with natural ecosystems, whereas most other croplands show significantly decreased production.

The second issue that Haberl *et al.* (1) address is how the productivity is appropriated by humans. Haberl *et al.* provide a detailed, geographic accounting of the human appropriation of NPP, showing large regions of the world where HANPP is between 60% and 100% of natural productivity. This analysis shows a more-detailed picture than the global-average report of Vitousek *et al.* (8). By combining these maps with consumption patterns (9), we have a detailed picture of the production and consumption of human-appropriated biological products across the Earth's land surface. Similar

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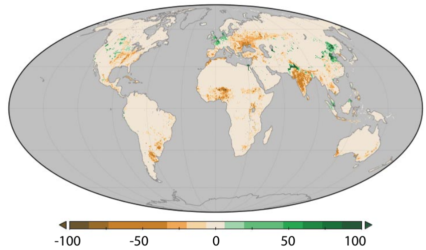

Fig. 2. Estimated change (percentage) in natural NPP from croplands. Noteworthy are regions where mechanization, irrigation, and fertilization increase cropland productivity above natural rates, while crop NPP in other regions is less than the natural NPP. Calculated from recent analyses of crop yields (10) and ecosystem productivity (11).

maps could, and should, be constructed for the world's marine and freshwater ecosystems.

These results provide the first detailed geographic description of the human appropriation of global NPP, representing a major breakthrough in the documentation of our presence in the biosphere. These data could be extended to show the fate of human-appropriated production; that is, what are these biological products, where are they going, and who is consuming them? As an example, we have examined patterns of global cropland productivity (10) and how it is allocated to different human uses, including food and nonfood products (Fig. 3 *Upper*). Furthermore, we can document the different economic roles of these products, including the percentage of crop NPP used for domestic consumption versus international exports (Fig. 3 *Lower*). Future analyses of the fate of ecological commodities would greatly enhance our understanding of global resource systems.

Naturally, there are limitations to how far we can interpret the human appropriation of NPP. Using productivity as a single "common currency" of ecological systems, whether for corn and coconuts or beef and barley, assumes that all biological products are equivalent. Obviously, looking beyond biomass, this is not true, and the local context of ecological production matters: What is grown in one place cannot always be substituted for what is grown in another. Perhaps it is time to move beyond these single units of production and consumption and more deeply consider the geographic, cultural, and historical context of our changing ecosystems.

Future research could instead focus on the patterns of ecosystem goods and services (12), both in terms of their patterns of ecological production and human consumption. In this way, the benefits of ecosystems can be expressed in terms of multiple (not always substitutable) metrics, including the production of crops, animal products, timber, and biofuel, plus the associated benefits of carbon storage and climate regulation, hydrological regulation and water purification, and disease vector moderation (7, 13).

In the meantime, the results of Haberl *et al.* (1) point to the staggering human impact on the biosphere. Building on the pioneering work of Vitousek *et al.* (8), this study pinpoints the geographic patterns of our impact, showing us a planet wildly transformed by our collective actions.

Given the magnitude of these effects, it is natural to ask how our use of terrestrial ecosystems can be sustained, let alone be expanded, as we consider the potential for future population growth, continued economic development (and associated changes in diet), and increasing interest in biologically based energy sources. Will the future growth of human land use come at the expense of continued ecological degradation (7) or rely on the unsustainable crutches of fossil fuels and fossil water?

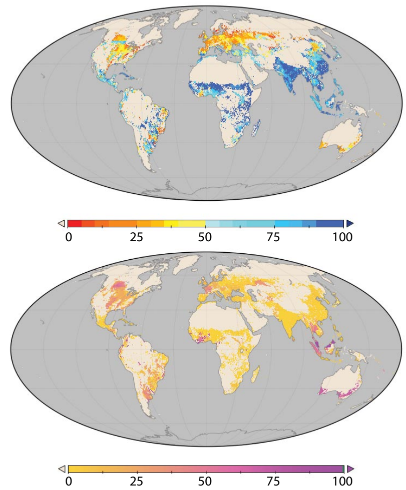

Fig. 3. Estimated fate of human-appropriated terrestrial ecosystem production. (*Upper*) Allocation (percentage) of crop production to food and nonfood uses. We show the percentage of crop NPP used to produce food that humans consume directly or indirectly in processed products. The majority of the nonfood portion is feed for livestock, although a lesser portion supports fiber or luxury crops, like cotton and coffee. The results are based on a recent analysis of crop yields (10). (*Lower*) Allocation (percentage) of global crop production to international exports. We show the percentage of crop NPP bound for international export; the remainder is for domestic consumption. The results are based on a recent analysis of global crop yields (10).

Ultimately, we need to question how much of the biosphere's productivity we can appropriate before planetary systems begin to break down. 30%? 40%? 50%? More?

Or have we already crossed that threshold?

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